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CATDBTREN PROJECT: NEW PREDICTION TOOL OF VIBRATION IMPACT FOR RAILWAY INFRASTRUCTURES

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A model to calculate the vibration impact is presented. Due to the complexity of the phenomena, the model has been divided in different calculation stages, according to the different physical processes of generation, propagation and transmission to the building. The result is obtained after the compilation of different partial results which, however, are related with each other.

1. Introduction

The generation of vibrations induced by trains, their propagation through the soil and their transmission into the building is a complex phenomenon because of the great number of parameters which are involved and the difficulty to know them all. For example, the behaviour of the vibration source, soil and track properties, building data and the interaction between all the stages (rolling stock, track, soil and building)[1,2]. Different methodologies have been proposed in order to predict vibration levels caused by induced train vibrations:

- Empirical methods: some empirical models can be found in bibliography[3], some of them are even used as a national reference calculation method in countries like Switzerland[4], Nordic Countries[5] or United States[6]. Models are usually based in some reference values of vibration level which can be modified depending on some characteristics of the elements involved in the calculation. The bases of the values are often obtained from statistical analysis of several measurement campaigns.
- Analytical methods: several theoretical approximations to the problem can be found in bibliography[7-9]. Their main shortcoming is that they usually can be only applied to one case, because every kind of track needs its own analytical model. Moreover, they are not very easily applicable at engineering level, with low data available.
- Numerical methods: based on Finite Element Method (FEM) or its combination with Boundary Element Method (BEM). Generally speaking, numerical methods can give good results but the lack of information about the vibration source and the material properties give also uncer-

tainty to results. They are also expensive in time and resources but they should be the method applied in those non-typical or very risky situations[10-12].

As a conclusion, however, it could be said that whichever the method used, there exists great variability in results, surely caused by uncertainties in the data[13].

The CATdBTren project is carried out by a consortium composed by SENER (multidisciplinary engineering company, as leader member), Railtech (leading company for manufacture of track and anti-vibratory solutions), Railgrup (cluster of companies from the Catalonian railway sector) and Quantech (leading company in the development of CAE software). The Acoustic and Mechanical Engineering Laboratory of the Universitat Politècnica de Catalunya and the Technological and Research Centre of Manresa collaborate as associated research centres. Its main goal is to determine the vibration level under typical conditions using small amount of resources. Thus, numerical methods are excluded. On the other hand, empirical models present some characteristics that can not be applied directly in countries different than that from origin. Analytical models, as it has been stated, are not easy to apply even at small scale.

To overcome all these difficulties and to look for its application to big scale problems, a semianalytical model is proposed. The output of the model will be calculated as an addition of four different physical phenomena included in three different calculation stages, as it is shown in fig. 1.

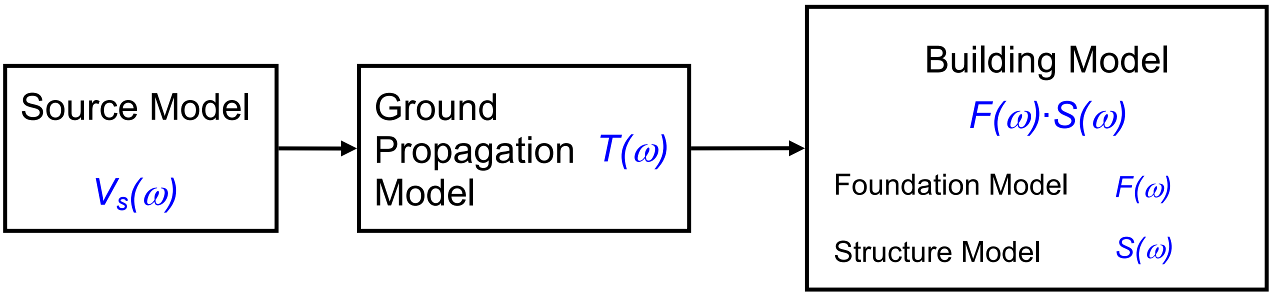

Figure 1. Calculation flow of the semianalytic model.

Final result will be one-third octave band vibration level inside building $V_r(\omega)$, and will be calculated from the ground vibration level at track point $V_s(\omega)$, modified by the transfer functions of propagation through the terrain $T(\omega)$, through the building foundations $F(\omega)$ and through building structure $S(\omega)$, according to the expression:

$$V_r(\omega)=V_s(\omega)\cdot T(\omega)\cdot F(\omega)\cdot S(\omega) \tag{1}$$

2. Source model $V_s(\omega)$

This submodel has the goal of giving the ground vibration level at track point $V(\omega)$. In order to obtain it, the road-rail contact force must be modelled which, at the same time, depends also on the train and track characteristics. Consequently, the vibration source model includes also two calculation stages: the track model and the wheel-rail contact force model, which however give only one value, $V_s(\omega)$.

2.1 Superstructure model

To know the vibration level at near ground due to railway transit, the dynamics of superstructure is the most important factor. Basically, there are two types of models in bibliography: the continuous model[1,2,14,16] and the discrete model[15,17]. The difference between these two approaches resides on the treatment of sleepers, considering these like a continuous or a discrete foundation, respectively.

The proposed analytical model is a simplification of the typical discrete model, where the rail track is taken like a punctual mass. The stiffness and damping coefficients below the rail track of this equivalent system will be calculated by means of the application of a force of known amplitude and phase. Over the rail track the model is completed with the rail-wheel contact force (see Fig. 2.2), the wheel (another punctual mass), the bogie primary suspension (a damped spring) and the static force (weight) of the train. Therefore, the model of contact force is part of the superstructure model. The train is considered like a fixed solid: its natural frequencies are much lower than the excitation frequencies of that contact force. The resulting model is a 4DOF system which includes the vertical motion of the wheel, rail, sleeper and ground.

2.2 Analytical-Statistical source model

An analytical model, based in the Hertz theory of elastic contacts[18,19], is presented here. This analytical approach calculates the contact force by means of the wheel-rail deformation δ; this deformation is function of the vertical motion and the irregularities of both rail track and the wheel. The Hertz theory is based in this expression:

$$F(t) = k_{Hertz}\delta^{3/2} \tag{2}$$

where k_{Hertz} can be calculated by knowing the geometry of the contact.

Several authors show that the irregularities of rail and wheel could be considered a zero mean gaussian isotropic random field in the spatial domain, and a normal stationary ergodic random process in the time domain. So, the roughness can be described by its power spectral density, in the frequency domain[20,21]. This description briefs the roughness profile data in a very useful way.

However, each rolling stock unit has a unique roughness profile which depends mostly on the date of the last maintenance procedure and other factors such as the number and intensity of braking. Hence, as can be seen experimentally, each unit produces a unique vibration spectrum, as can be seen in Figure 2.

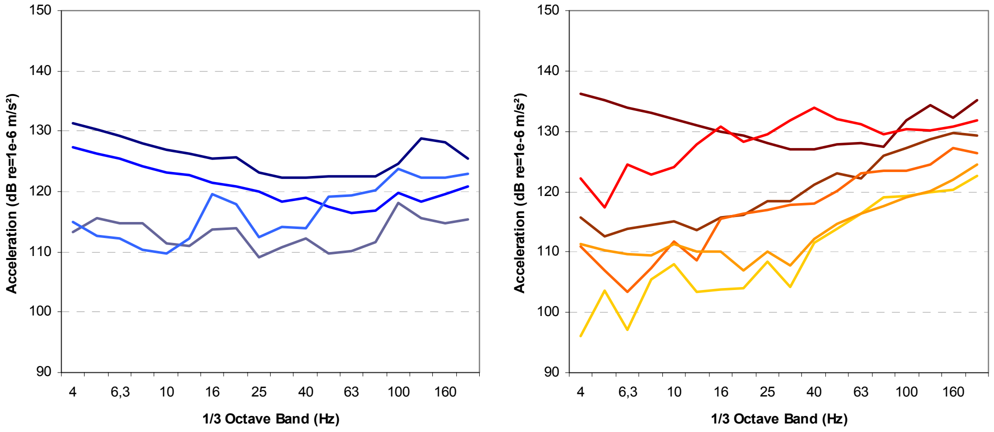

Figure 2. Rail vibration levels measured for four regional trains (left) and for six freight trains (right)

In this case it can be observed variations up to 18 dB and 51 dB (regional and freight train, respectively) which suggest the existence of a strong statistical behaviour. Therefore it becomes possible to define a statistical vibration generation model which would include mean and variance data for each typology of rolling stock. Defining this kind of models will require measuring a large quantity of units in a large set of locations. Finally it would be possible to quantify the expected vibration values in the 95% confidence range. Moreover, comparing these statistical data for different rail fastening systems it becomes possible to infer the influence and the vibration isolation efficiency of each substructure system.

Finally, if one transfer function between the contact force and the rail vibration level is available (measured or predicted using a FEM model), it is possible to obtain the characteristic contact force. As an example, figure 3 shows the statistical contact force calculated for regional and freight rolling stock (coloured areas correspond with the 95% confidence range).

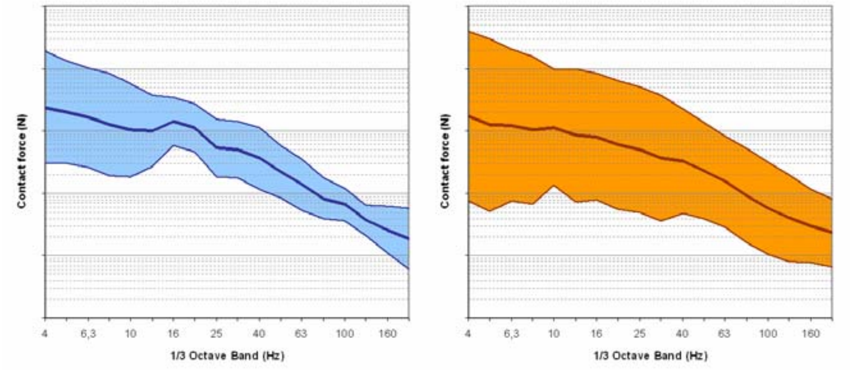

Figure 3. Calculated statistical contact force for regional trains (left hand) and for freight trains (right hand). Thick line: mean value; coloured areas: 95% confidence range.

These empirical (if a measured transfer function was used) or *pseudo*-empirical (if a FEM model provided the transfer function) force spectra can be used both for validating the contact force results obtained using the methodology detailed in the section 2.1 and for vibration impact prediction using rail-substructure numerical models.

3. Ground propagation model *T(ω)*

The outcome of this stage will be a transfer function *T(ω)* from the vibration level at the superstructure to the vibration level at any given distance as a function of the type of soil and superstructure. The type of superstructure is either surface or underground railway.

3.1 Surface propagation

The propagation of vibration can be modelled by the expression developed by Lamb[2] and later applied by Barkan[6] which gives the vibration amplitude at any point *b* provided the vibration amplitude at a certain point *a*:

$$v_b = v_a \cdot \left(\frac{r_a}{r_b}\right)^{\gamma} \cdot e^{\alpha\cdot(r_a - r_b)} \tag{3}$$

In this expression, γ is a geometric attenuation coefficient ranging values of 0.5, 1 or 2 depending on the type of source and wave[1], and α is a material damping coefficient, which depends on the characteristics of the soil and the frequency of the vibration.

The approach used by some authors[23-25] has been to treat a train as an intermediate case from the point and infinite line sources, finding a value for γ for a train source. But a surface train is a moving multipoint source which does not follow Equation 3. This fact can be seen from the simple case of three static point sources, one centred on the line of measurement and the other two at distances $-x_1$ and x_1. The sum of the three static point sources is the sum of three Equations 3 which give the following propagation law:

$$v(r) \propto (x_1^2 + r^2)^{-\gamma/2}\, e^{-\alpha\sqrt{x_1^2+r^2}} + r^{-\gamma} e^{-\alpha r} \tag{4}$$

One can see that the effects of the geometric and material damping coefficient are interlaced in the term $e^{-\alpha\sqrt{x_1^2+r^2}}$. As a matter of fact, the geometry of the source is given by its length, i.e. x_1, and in this simple case it can not be isolated from the material attenuation term, which is the exponential term on α. This means that it does not exist a value of γ for a multipoint source.

This project considers the train as a moving multipoint source and calculates the vibration amplitude at a given point from an algorithm that sums *n* Equations 3 for point sources (γ=0.5).

3.2 Underground propagation

In the case of an underground source and its effect on the surface, it appears the complexity of the generation of Rayleigh waves from the reflection of P and S waves on the edge of the propagation half-space, thus, making the application of Equation 3 also not suitable for this type of source. On the other hand, experimental data[26] show that the tunnel has an important effect on the surface vibration pattern attenuating the propagation, mostly on the vertical of the tunnel itself and up to a certain distance.

In order to obtain a database of pre-calculated surface vibration amplitudes, as a function of the frequency, for different types of soil and different depths, the solution adopted is to use a finite element model in order to numerically simulate an underground train. A 2D FEM model for the tunnel-terrain set has been built that allows to simulate an infinite line source. The advantages of a 2D model over a 3D model consist in the calculus time and in the precision of the results. A 2D model allows having a smaller element size, in consequence the result can be analyzed up to higher frequencies, while at the same time it keeps the total number of elements low, well within the time and memory margins necessaries for the calculation. The disadvantage of using a 2D model is that, given its symmetry, it can only simulate infinite line sources. A vertical unitary force, constant in frequency, is applied at the centre of the tunnel so that a symmetric boundary condition can be used and only half of the space has to be simulated. The terrain has an extension at its outermost and lowest sides have a non-reflective material. The amplitudes obtained from the model are finally calibrated using experimental data.

Figure 4 shows an example of the radiation pattern emerging from the tunnel. One can see that the tunnel casts a shadow in the vertical direction so that the vibration amplitude on the surface is higher at a certain angle from the vertical than in the vertical direction, in spite of being closer to the source. As the frequency grows the radiation lobe in the vertical direction gets more important, while the secondary lobe loses amplitude.

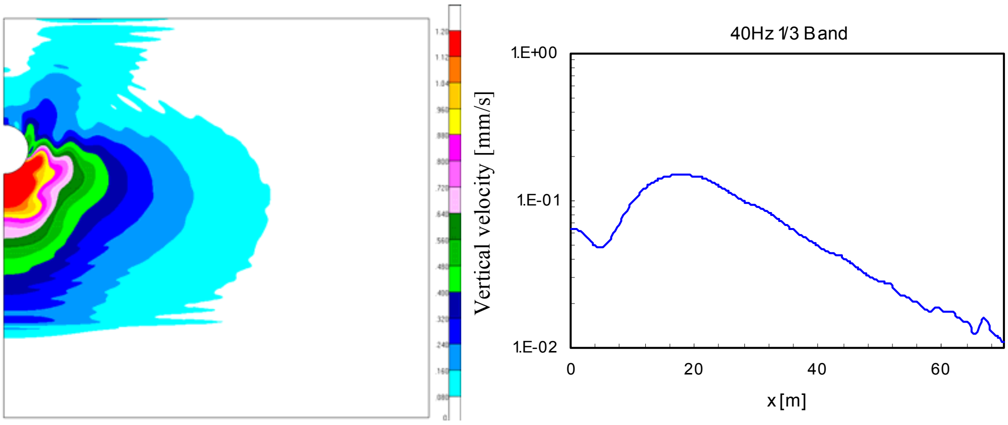

Figure 4. Figure on the left shows velocity amplitude at each point of the model for the one-third octave band centered on 40 Hz. Figure on the right shows vibration amplitude at surface level as a function of the distance, x, to the vertical of the tunnel for the same one-third octave band.

4. Building model

The building behaviour is approximated by two different transfer functions: foundation *F(ω)* and structure *S(ω)*.

4.1 Foundations *F(ω)*

Federal Transit Administration of the USA[5] considers always an attenuation of vibration, depending on the type of building, except in case of foundation in rock. However there are authors[27] who consider different behaviour depending on the area, depth and stiffness of the foundation and the stiffness of the soil. This relationship also depends on the frequency, including the effect of resonance at low frequency. However, experimental measurements carried out in buildings of masonry and concrete structure suggests an attenuation of about 0 dB between 1 to 80 Hz (Fig. 5). Due to the divergent results, the area near of ground-coupled building will be treated with FEM[28,29] in order to assess the influence of the dimensions and depth of the foundations and the soil stiffness in the ground-coupled building.

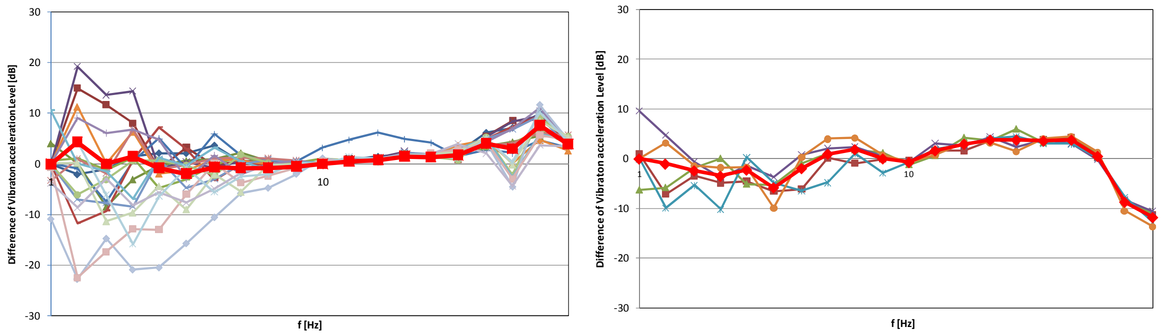

Figure 5. Difference level of vibration acceleration between inside and outside of building for masonry building (left) and concrete building (right)

4.2 Structures *S(ω)*

At this stage there are two parts: relationship between transmission of vibrations and heigh of the building and the behaviour of a representative floor.

Regarding de former, some authors have found an attenuation of vibrations of 1 to 2 dB/floor[30], 3 dB/floor for masonry buildings and buildings for light attenuation[31], and 1 dB/floor in buildings of masonry and a reduction of 5 dB in all floors in concrete's buildings[32]. Experimental measurements carried out show that there are amplifications for both types of buildings studied (Figure 6), with amplifications from 6.3 Hz. In masonry buildings, at first floor, there are amplifications of the vibration that are smaller for higher floors. In concrete buildings there are amplifications of the vibration on the first floor which remains constant for upper floors

Regarding the behaviour of the floor, FTA[5] assigns the value of the vibration amplification of 6 dB. Some authors found floors resonances between 10 and 60 Hz[33], or between 20 and 30 Hz[30]. Measures show that first resonances are between 10 and 25 Hz with amplifications up to 15 dB. These frequencies depend on the stiffness of materials of construction, the load of the building, distance between columns, dimensions of the floors, walls and columns. FEM analysis can be used in order to calculate vibration response of structures, but the big scale of the physical plant and the frequency range suggest that a FEM-SEA approach could be a good compromise between quality of results and the numerical size of the problem.

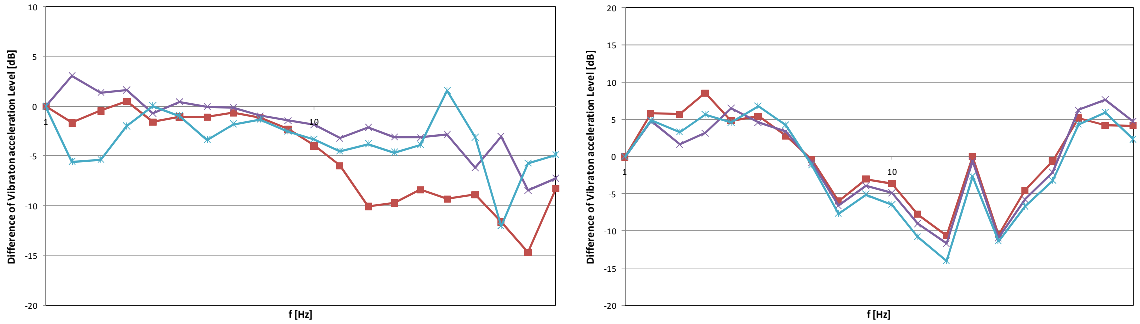

Figure 6. Variation of vibration level measured at center of different floors and ground floor for masonry building (left) and concrete building (right). Negative values indicate that vibrations at ground floors are smaller than the floor represented. □ First floor, x Second floor and 5 third floor.

The aim of studying the response of the structure and floors building is to get as vibrations vary according to materials and sections of the columns and walls, distance between columns and thickness of floors and ceilings.

5. Aknowlegmens

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